# Gravity mediated entanglement growth: spacetime superpositions in the lab and the possibility to probe Planck time.

*"On the possibility of laboratory evidence for quantum superposition of geometries"*, arXiv:1808.05842, C.Rovelli and MC

*"On the possibility of experimental detection of time discreteness"*, arXiv:1808.05842 , C.Rovelli and MC

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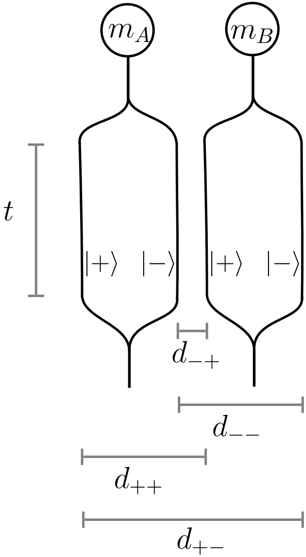
# A proposal for a feasible bench-top quantum gravity experiment from the quantum information community

- Two works simultaneously appeared: "*Spin entanglement witness for quantum gravity*", by Bose et al, and "*Gravitationally induced entanglement between two massive particles is sufficient evidence of quantum effects in gravity*", by Marletto and Vedral (PRL Dec 2017).
- The authors argued that if we observe entanglement growth in two particles due to their gravitational interaction alone, a feasible feat in the near term, we are compelled to conclude that the medium, the gravitational field, is also quantum.
- **What is this quantum feature of gravity that has observable consequences in laboratory conditions?** Effect originally derived in 'Newtonian limit'. We see here that taking into account GR, the effect arises because the gravitational field is set in a superposition of distinct macroscopic geometries.
- These phenomena seem to give meaning to the **Planck mass** $m_P$ **as a quantum gravity scale**. In particular, when the masses are at the Planck mass, the relative time dilation giving rise to the effect is at the Planck time scale $t_P$.

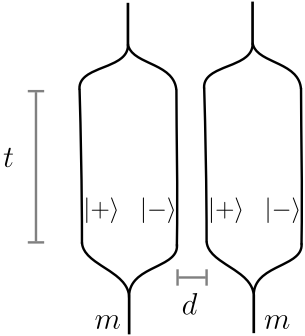
# The experiment




$m_A = m_B = m$

- Two masses with embedded spin each set in path superposition through a Stern-Gerlach type apparatus. Say each mass $A$ and $B$ prepared in $|\psi\rangle = \frac{1}{\sqrt{2}}(|+\rangle + |-\rangle)$ initially (zero entanglement).
- Work in static limit: relevant part is evolution by $e^{i\frac{Et}{\hbar}}$ of the quantum state during laboratory time $t$.
- There are four quantum branches : $++$,$--$,$-+$, $+-$. The state $|-+\rangle \equiv |-\rangle_A \otimes |+\rangle_B$ picks up a relative phase difference $\delta\phi$ wrt to the other branches because of an interaction mediated by gravity alone.
- Out state entangled: gravity mediated entanglement growth. The correlations of the spins witness the entanglement.

# Newtonian approximation




The gravitational energy of two masses $m$ at distance $d$ is

$$E_g = \frac{Gm^2}{d}$$

Evolution of the $|-+\rangle$ branch when in path superposition picks up a phase difference

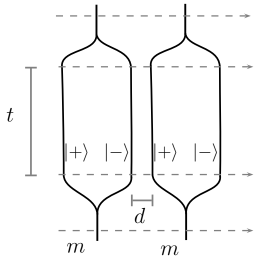
$$e^{i\delta\phi} = e^{i\frac{E_g\,t}{\hbar}}$$

This gives

$$\boxed{\delta\phi = \frac{Gm^2 t}{d\,\hbar}}$$

The above relation can be derived using time dilation.

# The effect is due to spacetime set in a superposition




$$|\Psi_f\rangle \propto \big(|{+}{+}\rangle + |{-}{-}\rangle + |{+}{-}\rangle + e^{i\delta\phi(t,m,d)}\,|{-}{+}\rangle\big) \otimes |g\rangle$$

$$|\Psi_2\rangle \propto |{+}{+}\rangle\,|g_{++}\rangle + |{-}{-}\rangle\,|g_{--}\rangle + |{+}{-}\rangle\,|g_{+-}\rangle + e^{i\delta\phi(t,m,d)}\,|{-}{+}\rangle\,|g_{-+}\rangle$$

$$|\Psi_1\rangle \propto |{+}{+}\rangle\,|g_{++}\rangle + |{-}{-}\rangle\,|g_{--}\rangle + |{+}{-}\rangle\,|g_{+-}\rangle + |{-}{+}\rangle\,|g_{-+}\rangle$$

$$|\Psi_i\rangle \propto |\psi_A\rangle \otimes |\psi_B\rangle \otimes |g\rangle$$

**Assumptions**: Gravity state space contains semiclassical states and their superpositions. GR valid at mesoscopic mass scales. **Regime**: weak field, low energy. **Simplifications**: neglect phases in other branches, stationary during $t$.

**Spacetime in superposition**: When the masses are in a superposition, the gravitational field is not in a semiclassical state. *Its state is a sum of four semiclassical states, each peaked on a diffeomorphically inequivalent metric*.

**Question: what is then the geometrical invariant that is being set in a superposition?**

# Superposition of metrics means clocks run at a superposition of time rates: relative time dilation

The classical spacetime sourced by the two masses is approximately a static weak field configuration. That is, in some coordinate system the metric takes the form:

$$\mathrm{d}s^2 = -\left(1 + 2\phi(\vec{x})\right)\mathrm{d}t^2 + \mathrm{d}\vec{x}^2$$
$$\phi = \phi_A + \phi_B$$
$$\phi_{A,B} = -Gm/r \quad r > R$$
$$\phi_{A,B} = -Gm/R \quad r < R$$

where $R$ is the mass radius. Inside each particle

$$\mathrm{d}s^2 = -\left(1 - r_S/R - r_S/d\right)\mathrm{d}t^2 + \mathrm{d}\vec{x}^2$$
$$r_S = 2Gm/c^2$$

$$\begin{aligned}\tau &= \int_0^t \mathrm{d}\tau \\ &\approx \sqrt{1 - \frac{2Gm}{c^2 R} - \frac{2Gm}{c^2 d}} \int_0^t \mathrm{d}t \\ &\approx \frac{1}{2}\left(2 - \frac{r_S}{R} - \frac{r_S}{d}\right) t \ , \ r_S = \frac{2Gm}{c^2}\end{aligned}$$

$$\delta\tau = \frac{1}{2}\frac{r_S}{d} t = \frac{Gmt}{dc^2}$$

Relative time dilation $\delta\tau$ due to the gravitational interaction between the two masses. Since proportional to ratio $r_S/d$ it corresponds to a tiny time interval, which however can be picked up by interference.

# Gravity mediated entanglement growth is the development of a relative time dilation between quantum branches

Relative time dilation $\delta\tau$:

$$\delta\tau = \frac{1}{2}\frac{r_S}{d}t = \frac{Gmt}{dc^2}$$

Relative quantum phase $\delta\phi$:

$$\delta\phi = \frac{mc^2\delta\tau}{\hbar}$$

Rearrange constants:

$$\boxed{\delta\phi = \frac{m}{m_P}\frac{\delta\tau}{t_P}}$$

**Indirect $\delta\tau$ measurement: fix $m$, measure $\delta\phi$, deduce $\delta\tau$.**

**Role of Planck mass**: by directly manipulating quantum superpositions of particles that interact gravitationally with masses close to the Planck mass, we indirectly probe through interference proper time intervals at the Planck time scale.

# Plug in numbers for $\delta\tau$

Experimental parameters claimed feasible with current technological capabilities: $d \sim 10^{-4}m$, $t \sim 1s$, $m \sim 10^{-6}m_P$

$$\delta\tau = \frac{Gmt}{dc^2} = 10^{-38}s = 10^6 t_P$$

This is an incredibly small time interval, already not too far from Planck time. We have seen that according to GR, gravity mediated entanglement growth allows to indirectly measure $\delta\tau$ through interference.

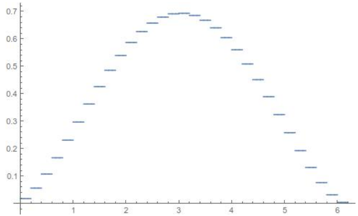
For comparison, precision direct measurements of time with atomic clocks are currently at $\sim 10^{-18}s$, a twenty order of magnitudes difference!

Notice that the relative time dilation probed is determined by the mass alone:

$$\delta\phi = \frac{m}{m_P}\frac{\delta\tau}{t_P} = \pi$$

$$m \sim 10^{-6}m_P \quad \Rightarrow \quad \delta\tau \sim 10^6 t_P$$

# Is $\delta\tau$ continuous when $m \sim m_P$? Quantum levels in entanglement entropy?




$I$ for the ansatz $\frac{\delta\tau}{t_P} \in \mathbb{N}^+$ and mass $m = 0.2\, m_P$.

$$\boxed{\delta\phi = \frac{m}{m_P}\frac{\delta\tau}{t_P}}$$

Consider the simple ansatz, that $\delta\tau$ takes values as multiples of Planck time. Quantum levels apear in the entanglement entropy since $I = I(\delta\tau)$.

The further we move to sub-Planckian masses, the number of quantum levels increases, becoming a continuous curve for $m << m_P$.

# Summary

- Quantum superposition of geometries can be achieved in the lab and has observable effects.
- The proper time intervals involved in the pursued experimental realization are of the order of a million Planck times, twenty orders of magnitude above atomic clock precision.
- When the superposed masses are close to the Planck mass we might be probing the structure of time at the Planck scale.
- Perhaps the current experimental push aiming to explore quantum phenomena in macroscopic objects and the 'border' between quantum and classical world will provide a **new avenue for QG phenomenology: the physical regime of non relativistic matter energy and weak gravitational field**.

# Directions

- Simulation of effect with photonics. Make precise why the 'quantumness' of the medium gives rise to the phenomenon.
- If only discreteness of time is searched, detecting entanglement is not relevant. What are alternative experimental setups?
  $\delta\phi = m\ \delta\tau \rightarrow \int dx^3 \rho(x)\delta\tau$
- Are there significant quantum corrections to $\delta\phi$ at $m \sim m_P$ from QG theory?
- The Gravitational Quantum Switch also requires superposition of spacetimes to be implemented with 'one-use' channels. What replaces diffeomorphism invariance in this regime?
- Imagine we do detect the existence of superpositions of spacetimes, a non-perturbative effect. We are compelled to learn how to do physics on a superposition of spacetimes. **There are is a host of interesting questions and conceptual issues that arise already at the level of weak gravitational field and non-relativistic matter! Perhaps much more so when spacetime is sourced by Planck mass scale matter distributions.**